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ESTIMATING PLUME DISPERSION - A RECOMMENDED GENERALIZED SCHEME

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1. INTRODUCTION

The following discussion presents a scheme for estimating the vertical and horizontal Gaussian dispersion parameters for point sources whose release heights are greater than 10 meters. The scheme requires either estimates of or measurements of the standard deviation of the horizontal and vertical wind direction fluctuations at the effective height of release. During unstable conditions, the depth of the convectively mixed layer and the convective velocity scale are required as input to the scheme. During neutral/stable conditions, the scheme requires specification of the depth of surface based neutral/stable layer. Provisions are made for incorporating the induced dispersion resulting from buoyant plume rise and from horizontal wind direction shear in the vertical. No provisions are made for dispersion induced due to terrain interaction with the transport of the plume.

Concern was expressed over the misapplication of popular Gaussian dispersion parameter schemes for estimating dispersion from elevated releases in the summary by Hanna et al. (1977) of the American Meteorological Society (AMS) Workshop on stability classification schemes and sigma curves. The recent tank studies, that simulate convectively unstable conditions by Willis and Deardorff (1976, 1978), reveal two parameters that have significant impact on dispersion: (1) the depth of the convectively mixed layer, and (2) the convective velocity scale. These two parameters are not considered in the popular Gaussian dispersion parameter schemes presented by Smith (1968), Turner (1970) and Smith (1972). Data from the tank results, the second-order closure modeling results of Lewellen and Teske (1975), and the results of Draxler (1976) indicate that variations in dispersion occur as a function of effective release height. Nieuwstadt and Engdahl (1976) combined the three popular schemes mentioned above in order to account for the effects of release height and surface roughness on dispersion from point sources. The results of the AMS Workshop suggest that two of the schemes, Turner (1970) and Smith (1968) are valid for surface roughnesses of 3 to 30 cm and 100 cm, respectively. All three schemes have different definitions of stability; therefore, the synthesis of them as performed by Nieuwstadt and Engdahl (1976)

must be viewed with caution. Draxler's (1976) scheme for consistently handling both elevated and surface releases has modeled the vertical dispersion, σ_z , and the horizontal dispersion, σ_y , as:

$$\sigma_{z,y} = \sigma_{w,v} T F_{z,y}(T/T_i)$$

where $\sigma_{w,v}$ = the standard deviation of the vertical and horizontal velocity fluctuations;

T = the travel time;
 T_i = an empirical parameter related to the Lagrangian time scale which is a function of stability and release height;

$F_{z,y}$ = a universal function defined separately for σ_z and σ_y whose form changes with stability and release height.

Draxler's analysis assumed conditions were stationary and that conditions were vertically and horizontally homogeneous. Various suppositions were made due to the limited dispersion data available in order to specify the parameters required to estimate $F_{z,y}$. The scatter in the data prevented a detailed designation of $F_{z,y}$, but the analysis demonstrated a technique that could result in a practical scheme for estimating dispersion. Using the suggestions of the AMS Workshop, Irwin (1978) specified a universal function for vertical dispersion, F_z , to be used in the interim until the collection of more field data permits the creation of a more accurate scheme.

2. REVIEW OF INTERIM SCHEME

2.1 Lateral Dispersion

For lateral dispersion, the interim scheme uses the AMS Workshop recommendation of using Pasquill's (1976) results:

$$\sigma_y = \sigma_a X f_y(X)$$

where σ_a = the standard deviation of the horizontal wind direction fluctuations in radians;
 X = the downwind distance in meters.

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The universal function $f_y(X)$ was independent of release height and stability, as specified in table form by Pasquill (1976). Pasquill's table of values for $f_y(X)$ can be approximated as:

for $X \leq 10$ km:

$$[(1+0.0308X^{0.4548})]^{-1}$$

and for $X > 10$ km:

$$0.333(10,000/X)^{1/2}$$

where X is in meters.

Assumptions implicit in Pasquill's (1976) analysis are that the wind fluctuations are measured at the effective release height and that σ is computed over a time period (up to one hour) comparable to the averaging time of the concentration estimate. During unstable conditions, Pasquill (1976) suggests that measurements at the effective release height may not be necessary, since σ_a is only a weak function of height.

2.2 Vertical Dispersion

For unstable conditions, the interim scheme estimates the vertical dispersion as:

$$\sigma_z = \sigma_e X f_z(t_*, Z/h)$$

where σ_e = the standard deviation of the vertical wind direction fluctuations in radians;
 $t_* = T w_* / h$, nondimensional time;
 $w_* = u_* (-h/kL)^{1/3}$, convective velocity scale, m/s;
 h = the depth of the convectively mixed layer m;
 k = the Von Karman constant, 0.4;
 L = the Monin-Obukhov length scale, m;
 u_* = the surface friction velocity, m/s;
 Z = the effective height of release.

The universal function f_z is depicted in Figures 1 and 2 for Z/h values less than 0.07 and greater than 0.25. Where Z/h values are between 0.07 and 0.25, a logarithmic interpolation is suggested. Only field data having direct measurements of σ and σ_a were used to specify the universal function f_z , which limited the data to Porton (Hay and Pasquill, 1957) and Project Prairie Grass (Barad, 1958; Haugen et al., 1961). In both cases, the depth of the convectively mixed layer was assumed to be 1000 m. To these data were added the tank data of Willis and Deardorff (1976, 1978) and the numerical data of Lamb (1978). The numerical data for Z/h of 0.025, 0.26, 0.50, and 0.71 have been developed by Lamb, but only the results for 0.26 are reported in Lamb (1978).

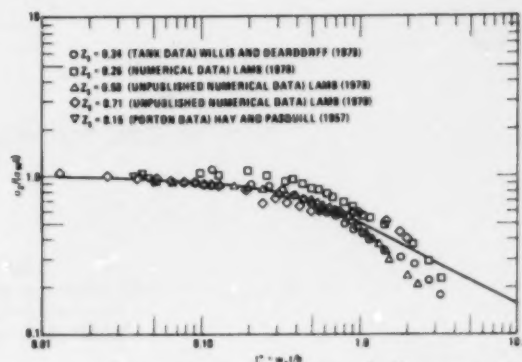


Figure 1. Values of $\sigma/\sigma_a T$ versus t^* for elevated releases during unstable conditions.

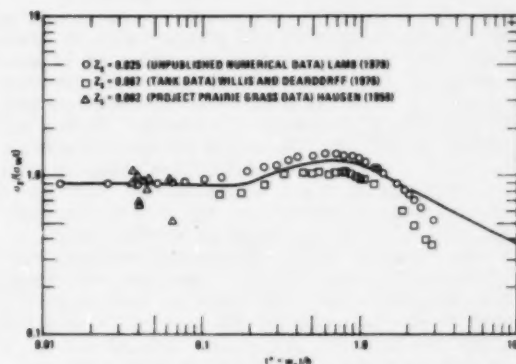


Figure 2. Values of $\sigma/\sigma_a T$ versus t^* for near-surface releases during unstable conditions.

For stable and neutral conditions the interim scheme estimates the vertical dispersion as:

$$\sigma_z = \sigma_e X f_z(T, Z)$$

where f_z is depicted in Figure 3 for Z values less than 50 m and greater than 100 m.

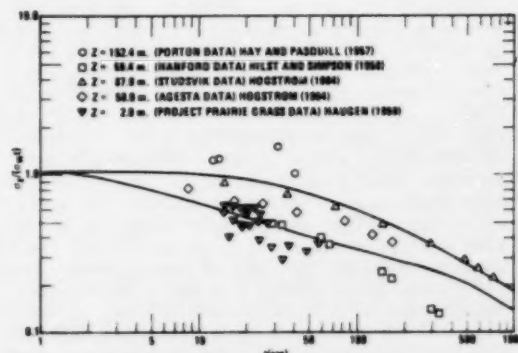


Figure 3. Values of $\sigma/\sigma_a T$ versus T for various release heights during neutral and stable conditions.

Where heights are between 50 m and 100 m, logarithmic interpolation is suggested. For the neutral and stable analysis, the Porton and Prairie Grass data were again the only field data to have both measurements of σ_z and σ_y . The near-neutral field data presented by Hogstrom (1964) and by Hilst and Simpson (1958) were adapted using Nickerson and Smiley's (1975) formulation for estimating u_w/u and Binkowski's (1978) formulation for estimating σ_w/u_w to approximate σ_z (which is a function of release height, stability, and surface roughness) as $(\sigma_w/u_w)(u_w/u)$. Estimates were used of the surface roughness, Z_0 , assuming $L = +\infty$.

In the limit for large travel times, the hand-drawn curves for f_z and f_z^{22} predict that σ_z becomes proportional to $T^{1/2}$; for small travel times, the hand-drawn curves predict that σ_z is proportional to T . When a limit to dispersion in the vertical exists, σ_z is effectively limited, thereby forcing f_z to become proportional to T^{-1} . The interim scheme was designed for use where limited mixing is accounted for in the dispersion equations. Hence, the representations of f_z shown in Figures 1 and 2 were not fitted to σ_z data values when limited dispersion effects were apparent.

If the effective height of the plume is higher than the convectively mixed depth, or higher than the surface based neutral/stable layer, σ_z is set to a minimum value of 0.01 radians. Releases at these heights are assumed to have little impact on surface concentrations, unless the material suspended aloft is brought towards the surface by fumigation. Though perhaps overly simplistic, this assumption should be adequate when conditions are steady-state and the plume transport is unaffected by terrain features.

2.3 Plume Rise and Wind Direction Shear

The induced lateral and vertical dispersion due to buoyant plume rise is estimated by using the results of Pasquill (1976) as suggested by the AMS Workshop. Pasquill (1976) proposes that the induced vertical dispersion due to buoyant plume rise, represented by effective σ_z , is roughly $\Delta h/3.5$, where Δh is the plume rise. The lateral and vertical dispersion are assumed to be affected equally by plume rise, see Cramer, et al. (1972). Pasquill (1976) incorporates the induced dispersion by adding variances (where the lateral dispersion squared equals the dispersion neglecting buoyancy squared plus the induced dispersion squared).

The lateral dispersion due to horizontal wind direction shear in the vertical follows Pasquill's (1976) suggestions as recommended by the AMS Workshop. The induced dispersion, represented by effective σ_y , is roughly $0.173 \Delta \theta X$, where $\Delta \theta$ is defined as the horizontal wind direction shear in radians within the layer containing the plume. Pasquill incorporates this induced dispersion by adding variances, but he suggests that this effect is so small it does not need to be introduced for downwind distances less than 20 km. In order to avoid the possibility of a step change in the lateral dispersion at 20 km the interim scheme considers the effect at all

downwind distances. The vertical dispersion is used to define the thickness of the plume at each downwind distance.

3. ESTIMATION OF INPUT PARAMETERS

The following section outlines some suggested techniques for estimating σ_y , σ_z and w_e if these are not available from on-site meteorological data. The vertical profiles of σ_y and σ_z are functions of L and Z . In addition, during unstable conditions, both h and w_e are required in order to properly characterize σ_y and σ_z . Using the Richardson number, when measured as outlined later, to estimate L should work as well as on-site measurements of L . The technique presented to estimate L using P-G stability class is a less reliable procedure. Use of P-G class estimates of L may prove useful for broad comparisons and characterizations; however, for case studies such estimates of L may be so unreliable as to obscure any benefit which might be gained in using the interim scheme over presently used schemes which are simpler to use.

3.1 Estimation of w_e

In order to estimate f_z for unstable conditions, w_e must be calculated. It can be derived if u_w , L and h , are known, but u_w is often not known. However, w_e can be estimated by using Figure 4, given Z/h and $\sigma_z = \sigma_y u$, where u is the mean wind speed at height Z . The relationship between σ_z/w_e and Z/h is depicted in Figure 4, which illustrates the data used by Willis and Deardorff (1974) and Kaimal, et al. (1976).

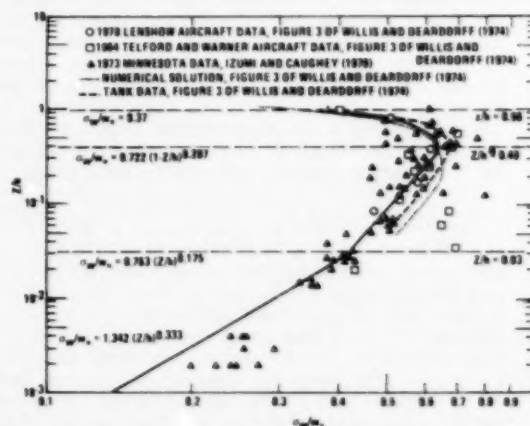


Figure 4. Vertical profile of σ_z/w_e for fully convective conditions, where σ_z and w_e are the standard deviation of the vertical velocity fluctuations and the convective velocity scale and h is the depth of the convectively mixed layer. Solution shown as solid line was derived, for z/h greater than 0.03, from hand-drawn fits to the data values. Solid line, for z/h less than 0.03, is prediction for free convection conditions, see equation 17 of Kaimal et al. (1976).

3.2 Estimation of Z_0

It is adequate to estimate the surface roughness length, Z_0 , using tables which give typical Z_0 values based on land-use, such as given in Figure 7 of Counihan (1975). Evaluate the land-use in the vicinity of the source, say within 3 km. Typically, Z_0 is about 0.1 m for rural applications and Z_0 is about 1.0 m for urban and forested applications.

3.3 Estimation of σ_w

On-site measurements of $\sigma_w = (\sigma_w/u_w)(u_w/u)$ at the effective release height $h_e = h_s + \Delta h$, where h_s is the stack height, are not always available. The primary difficulty in estimating σ_w lies in properly characterizing σ_w/u_w (see Panofsky, 1973). The semi-empirical relationships by Nickerson and Smiley (1975) and Benoit (1977) that relate u_w/u to L , Z and Z_0 , perform quite well, even when $|Z/L|$ is of order 3. This performance is fortuitous since similarity relationships usually break down at $|Z/L|$ values of order 2. A recent result by Panofsky, et al. (1977):

$$\sigma_w/u_w = (12 - 0.5h/L)^{1/3}$$

demonstrated the importance of the mixed layer depth in properly characterizing σ_w/u_w during convectively unstable conditions. For neutral conditions, σ_w/u_w is rather site specific with values ranging from 1.4 to 2.2, (Ariel' and Nadezhina, 1976). Panofsky (1973) suggests this range is due to variations between sites in the mesoscale features. Binkowski's (1978) results indicate σ_w/u_w to be a weak function of Z/L during stable conditions, departing only slightly from its neutral value. Using data from both the Kansas 1968 field experiment (Izumi, 1972) and the Minnesota 1973 field experiment (Izumi and Caughey, 1976), Binkowski (1978) found the neutral value of σ_w/u_w to be 1.78. More accurate characterizations of σ_w will evolve; but in the interim, σ_w/u_w can be used to approximate σ_w by using Panofsky's above mentioned equation during unstable conditions and by setting σ_w/u_w equal to 1.78 during neutral and stable conditions.

3.4 Estimation of σ_e

When on-site measurements of σ_e at the effective release height are not available, σ_e can be estimated as $(\sigma_w/u_w)(u_w/u)$. Given a measurement of u at some reference height, perhaps 10 m, u_w can be estimated using the semi-empirical relationships mentioned previously for u_w/u . For unstable conditions, w_w can then be calculated and σ_e can be estimated using the results depicted in Figure 4. For neutral and stable conditions, the results of Binkowski (1978) can be used where:

$$\sigma_w/u_w = \left[\frac{\phi_m - Z/L}{1.2 f_m} \right]^{1/3}$$

where $\phi = 1+5Z/L$, the nondimensional wind shear for neutral and stable conditions.

For $0 < Z/L \leq 2.0$:

$$f_m = 0.4 \left[1 + 3.39Z/L - 0.25(Z/L)^2 \right]$$

and for $Z/L \geq 2.0$:

$$f_m = 0.4 \left[6.78 + 2.39(Z/L - 2) \right]$$

3.5 Estimation of L

The preceding discussions have assumed that on-site measurements of the Monin-Obukhov length scale, L , were available. However, various means exist to estimate L when given the Bulk Richardson number, $R_i = g\Delta T/(T u^2)$, where g is the acceleration due to gravity, T is the ambient air temperature (Kelvin) at height Z , u is the wind speed at height Z , and ΔT is the temperature difference (Kelvin) between a sensor at height Z , and a sensor at some lower height, Z_1 . Using the formulations presented by Nickerson and Smiley (1975) and Benoit (1977) that relate the vertical profiles of temperature and wind speed to L and Z_0 , on-site measurements of R_i can be related to L (Irwin, 1978). The preceding method of estimating L , given R_i and Z_0 , is effective if Z is less than $|L|$. This limitation reduces the upper measurement height in determining R_i to little more than 10 m.

Often the only available characterization of stability is a P-G stability class (Turner, 1970). Golder's (1972) nomograms relating P-G class to estimates of L , given Z_0 , have been fitted to numerical relationships by Liu, et al. (1976) which were adapted for use here as:

P-G class	$1/L = a Z_0^b$
	$a \quad b$
A	-0.0675 -0.1029
B	-0.03849 -0.1714
C	-0.00807 -0.3049
D	0.0 0.0
E	0.00807 -0.3049
F	0.03849 -0.1714

where Z_0 and L are in meters.

4. MAXIMUM SURFACE CONCENTRATIONS

In order to investigate the effect of changes in surface roughness on concentration estimates as well as compare the results with estimates using other dispersion parameter schemes, the interim scheme was implemented using the procedures outlined above to approximate the required input data as a function of P-G stability class. The plume rise was assumed to be zero. Mean values of the horizontal wind direction shear for each P-G stability class were estimated using the pibal data and the Richardson number data collected at O'Neill, Nebraska in 1953 (Lettau and Davidson, (1957), as:

P-G Class	Horizontal Wind Direction Shear ($^{\circ}/100\text{ m}$)
A	5
B	10
C	15
D	20
E	25
F	35

The estimates of the lateral and vertical dispersion were substituted into the Gaussian plume equation (Turner, 1970) so that the maximum surface concentration and the distance to the maximum could be estimated where:

$$C = \frac{1}{\pi \sigma_y \sigma_z} \exp \left[-h_e^2 / (2\sigma_z^2) \right]$$

where $C = XU/Q$, maximum surface concentration normalized by wind speed and emission rate, m^{-2} ;

$h_e = h$, since plume rise is assumed to be zero.

The results for three surface roughnesses, Z_0 of 0.03, 0.10, and 1.0 m, are depicted in Figures 5a, 5b, and 5c. Figure 5d depicts the normalized maximum surface concentration and the downwind distance to the maximum as would be estimated using the P-G dispersion parameters. This graph is the same as Figure 3-9 of Turner (1970). The P-G scheme is based on dispersion data from various sites, with surface roughnesses varying from 0.03 to 0.30 m. Hence, at least for the lower release heights, Figures 5a and 5b should relate to Figure 5d. The main effect of increasing the surface roughness from 0.03 to 0.10 m, when comparing Figures 5a and 5b, is to decrease the downwind distance to the maximum surface concentration, with only minor changes in the maximum concentration estimates. For release heights below 50 m, the results depicted in Figures 5a and 5b are quite similar to those generated using the P-G dispersion parameters, Figure 5d. For the higher release heights, the results depicted in Figures 5a and 5b are again quite similar to the P-G results. Comparisons of Figures 5a and 5b with Figure 5d should be interpreted with some care. The lateral dispersion parameters used in the P-G scheme are most appropriate for concentration estimates of 3-minute averaging time, whereas the interim scheme lateral dispersion estimates, as implemented, are most appropriate for concentration estimates of 40 to 60 minutes averaging time. Thus, even though the results depicted in Figures 5a and 5b are numerically similar to the results depicted in Figure 5d, the lateral dimensions of the plume's impact on the surface, as estimated by the interim scheme, are larger than would be estimated by the P-G scheme. Therefore, concentration estimates that might be derived using the interim scheme for 3-hour and 24-hour averaging times are expected to be higher than would be estimated through the P-G scheme. For comparison with the results shown in Figure 5c, maximum surface concentrations for a 100 m release

height were estimated using the Brookhaven dispersion parameters (Smith, 1968) and overplotted as 0 on the figure. These parameters, which are valid for concentration estimates of 1-hour averaging time, are based on releases of tracer from the 108 level of the Brookhaven meteorological tower, where the site roughness is about 1.0 m. Figure 5c results compare well with the estimates using the Brookhaven parameters. The "kinks" in the neutral and stable results depicted in Figures 5a, 5b and 5c are due to the logarithmic interpolation used for release heights between 50 and 100 m. Such kinks do not occur for the unstable results, even though logarithmic interpolation was used. Presently, the stable results are considered tolerable, but improvement through the acquisition of more complete field data is needed.

5. CONCLUSIONS

The scheme presented for estimating the lateral and vertical dispersion parameters was developed to use on-site meteorological data. The techniques given for estimating data necessary to the scheme should be recognized as simplistic. They were not presented as substitutes for on-site measurements, but for occasions when the required data is unavailable. The semi-empirical expressions offered for estimating σ_y and σ_z during unstable conditions are valid within the convectively mixed layer, where $-h/L$ is greater than 10. The scheme also uses these expressions during slightly unstable conditions, which is not strictly valid; nevertheless, this use was deemed a reasonable sacrifice in order to construct a scheme that performs smoothly through unstable to neutral conditions. The semi-empirical expressions used to estimate u_s/u , σ_y , σ_z , and R_s for neutral and stable conditions are based on similarity theory. These expressions are valid for values of $|Z/L|$ less than 2; however, they are not strictly valid for elevated releases where $|Z/L|$ is greater than 2, because they exceed the Z/L data values used to formulate the expressions. Furthermore, during very stable conditions, the expressions may be invalid since conditions aloft may not be steady state or the flow may be decoupled from the surface conditions. The various sacrifices made in constructing the scheme from available resources highlight the AMS Workshop's conclusion that more observations are sorely needed in order to confirm existing hypotheses. Yet, the agreement of the P-G estimates and Brookhaven estimates with the interim scheme results suggests that the expressions as specified are reasonable. The direct benefit of using the universal functions, in specifying the dispersion parameters, as employed by Draxler (1976), is that results from various studies can be utilized. Considering the scarcity of detailed tracer data, the synthesis of results from various studies is necessary in order to incorporate the various suggestions and conclusions reached by the AMS Workshop (Hanna, et al., 1977).

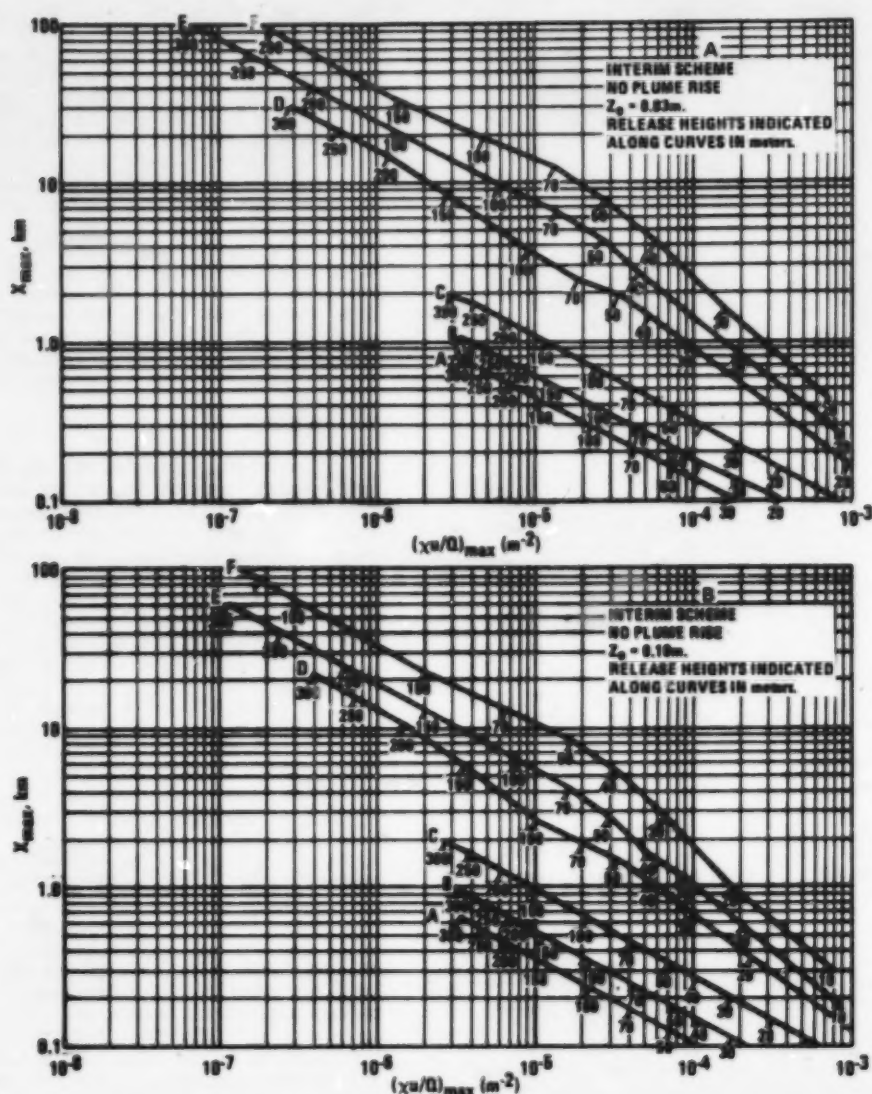


Figure 5. Distance of maximum concentration, X_{max} and maximum xu/Q as a function of stability (curves) and effective height (meters) of emission.

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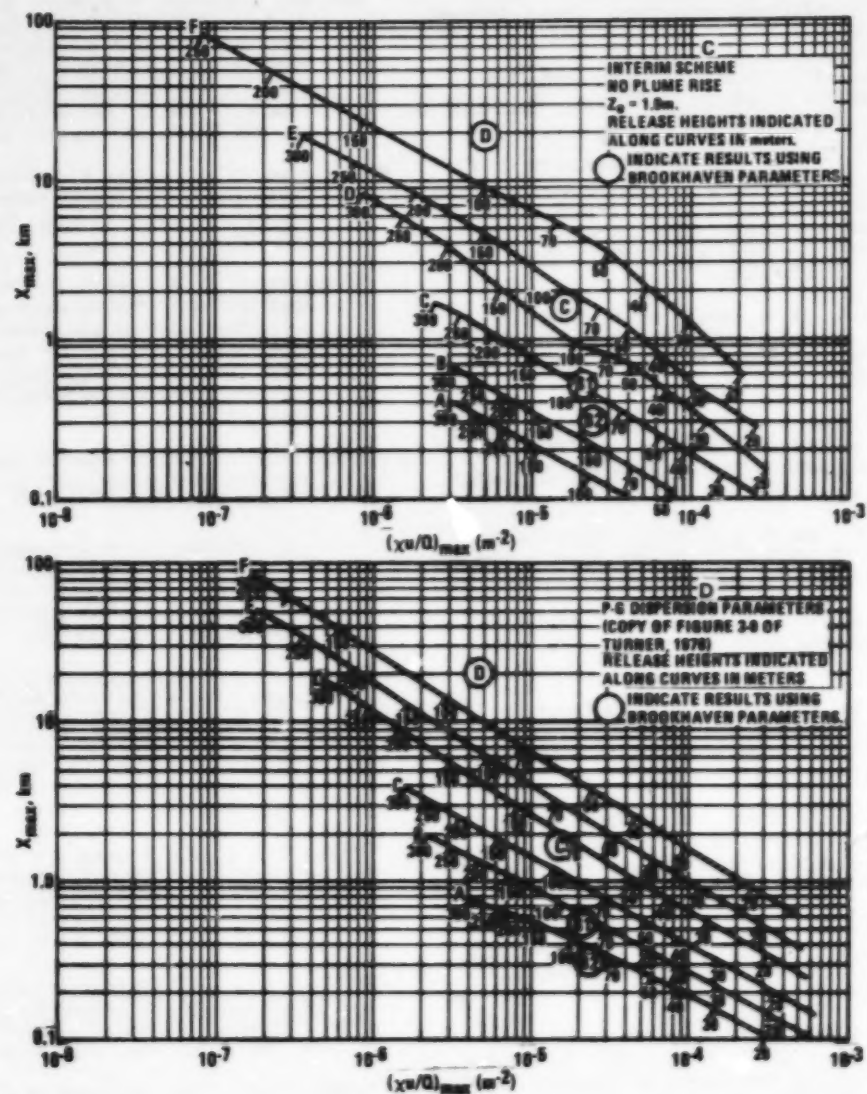


Figure 5 (cont.). Distance of maximum concentration, X_{max} , and maximum xu/Q as a function of stability (curves) and effective height (meters) of emission.

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